pressed into good contact with the aluminium discs, served as a means of transmitting current through the electrolyte between the discs. The frequency was 73, the temperature 18° C., and square root of mean square value of current about 1 ampere. No perceptible difference was observed in phase difference between potential and current when the discs were rotated and at rest in the electrolyte.

The conclusion is that the effect investigated in this paper takes time to develop, and is not fully developed with alternate currents of frequencies sixteen and ninety-eight complete periods per second. It can be increased by increasing the current density for a given film, and is greatly influenced by temperature. The metal aluminium with its film is suitable for use as the plates of condensers, if due regard be given to current density and temperature. It might in some cases be found useful as an equivalent to a metallic resistance.

Messrs. Simpson, Greenbank, and Davy, Student Demonstrators in the Siemens Laboratory, King's College, London, have given me valuable assistance in the experimental part, and in the working out of results. To these gentlemen I tender my thanks.

## "Contributions to the Study of 'Flicker.'" By T. C. Porter, Eton College. Communicated by Lord Rayleigh, F.R.S. Received May 13,—Read May 26, 1898.

Much work has already been done on this subject, though little of a quantitative character. Many observers have described the curious colour sensations which rapid alternations of light and darkness can excite under certain conditions, admirably exemplified in the "spectrum tops." Foremost amongst those whose experiments and writings have led to the present very general interest in the subjects of flicker, and of the sensation of light and colour, may be mentioned Helmholtz, Silvanus Thompson, Shelford Bidwell, Henry, Charpentier, and Rood; whilst the first to try experiments on the relative sensitiveness of the eye to flicker in light of different colours, seems to have been J. Plateau, who, however, employed pigments, and not the colours of the spectrum.

The writer's first experiments were made to ascertain the exact relative rotations at which the flicker just vanishes in the different colours of the same spectrum, and were carried out ($a$) as suggested by Professor Rood in his 'Modern Chromatics,' with a balanced, blackened, opaque disc, having a broad semicircular arc removed, and ($b$) on a cardboard disc, half black, half white, viewed in the different colours of the spectrum of the second order of a Rowland's plane diffraction grating of 14,434 lines to the inch. Two sources of light were employed, ($a$) direct sunshine, ($b$) lime-light. The results

are conveniently expressed by curves (fig. 1); along one axis of which the spectrum is plotted, on the other the rate of rotation of the disc.

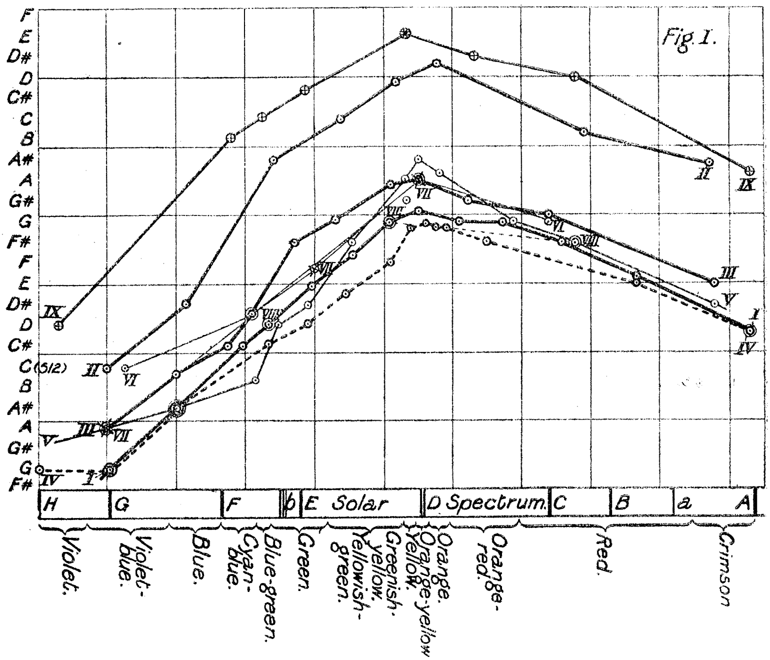


Fig. 1.

This last was found from the pitch of the note, obtained by blowing air gently through a known number of equidistant holes pierced in the circumference of the disc, and comparing these notes with those of a set of standard forks. Where the lime-light was used, great pains were taken to keep the intensity of the light constant throughout each experiment, though in these first experiments the intensity varied for the different curves. It may be well to point out that owing to the nature of the spectrum of lime, the orange is somewhat brighter and the blue and violet darker, relatively, than they are in sunshine. It is for a similar reason, as well as for others too obvious to mention, that the arc light was not employed. It will be seen, that in fig. 1, the intervals of the chromatic scale are plotted in equidistant order, and it should be remembered that the arithmetic increase in the number of revolutions to raise the pitch of the note from C (128 vibrations) to C (256), is only half that to raise it from C (256) to C (512), and so on. The effect of plotting on the axis of Y the actual number of revolutions, would be to make all the curves a great deal steeper. It seems necessary, too, to mention

that the writer's eyes are perfectly normal, and that he has a good ear. There are so many experimental details, that to describe fully a single observation, and to state the reasons for the many precautions which must be taken if the result is to be of any value, would take up so much space that the writer thinks it best only to mention a few of the more important:—The same spot on the lime was never used twice; the width of the slit was kept unaltered; each disappearance of flicker was witnessed by two, sometimes three, observers; the same time as nearly as possible was maintained between the observations, and used in making them, in order that the retina as well as the lime might be in approximately the same condition for each; the room was completely dark* and the eyes rested between the observations, never looking at any bright objects, and, above all, not at the lime; the oxygen and coal gas were conveyed by special metal pipes from gasometers in which they were stored under constant pressure outside the building, but since the composition of both gases is liable to variation, the intensity of the light was maintained constant, by regulating the supply of the gases till the flicker of a half and half disc in the yellow vanished at the same speed of rotation (generally A′). After every set of experiments, to make sure that the illumination had not sensibly changed, the note for vanishing flicker in the yellow was again observed. Experience teaches that the blue-green is rather better than the yellow for this purpose, and accordingly it was used in later experiments. Not more than two curves, often only one, were drawn in twenty-four hours, and to check the effects of contrast in consecutive experiments in different colours, a curve was drawn (*a*) by taking the colours of the spectrum from red to violet and *vice versâ* in their natural order, and (*b*) by finding the pairs of colours on either side of the yellow for which flicker vanished at the same rate of rotation. The results of experiments made thus agree very closely, and the writer may say here that throughout the eight years during which the research has been carried on, the feeling has steadily grown that in subjective vision we have to do with immutable quantities, capable of exact measurement, and which vary but slightly, if at all, with different people.

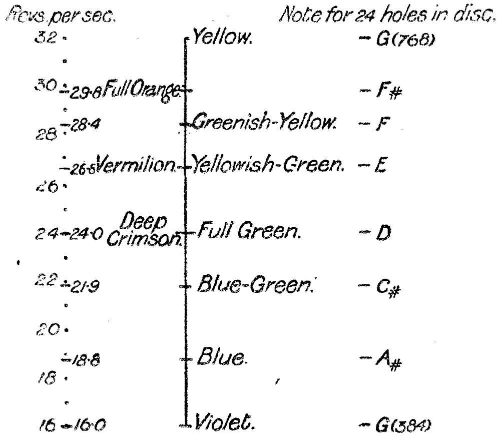
A glance at the curves in fig. 1 will show that there is a very great difference in the rates of rotation necessary for the disappearance of flicker in the different parts of the spectrum, the speed for the yellow being very nearly *double* that for the violet.

Also, that on each side of the yellow the rate decreases, until the flicker disappears for the last distinctly visible red at the same rate at which it vanishes for the full green.

Fig. 2 presents this last fact in a somewhat different way, and, if

* So far as external light is concerned.

FIG. 2.




anything, more clearly; the yellow and the violet—the two extremes so far as the present considerations go—are placed at the top and bottom of the central vertical line, and the number of rotations per second necessary for flicker just to vanish, given in the column on the left, is seen to be (*for this half-white, half-black disc*) 32 for the yellow, and 16 for the violet, and 24 for the last pair of colours—crimson and full green. The comparative rates of rotation for these colours thus bear the ratios of 2 : 3 : 4, which are easily remembered.

To return to fig. 1. The curves II and IX lie considerably above the others: they are the expression of observations made, as suggested to Professor Rood by Dr. Woolcott Gibbs, by viewing the spectrum through a rotating disc having a sector of 180° removed, using a telescope. Though the *form* of these two curves is practically the same as that of the others, their higher position, due to the superior intensity of the light received by the eye in this direct vision method, proves clearly what is already well known for white light, that the speed necessary for the disappearance of flicker increases with increase of the intensity of the light, whatever its colour may be. No. II is for lime-light, No. IX for sunlight, the rays of the sun being reflected through the slit by means of a heliostat.

Of the other curves in fig. 2 not much need be said; they are all for lime-light, the spectrum being thrown on the rotating cardboard disc half white and half black. The writer has thought it better not to smooth the curves in any way.

These curves, then, not only confirm the already known fact that

the stimulus given to the retina lasts *undiminished* a shorter time for the yellow than for any other colour, but they give the very approximately exact relative "last" for the different colours. The general form of the curves following very closely the curve which expresses the luminous intensity of the spectrum obtained by Newton, Abney, and others.

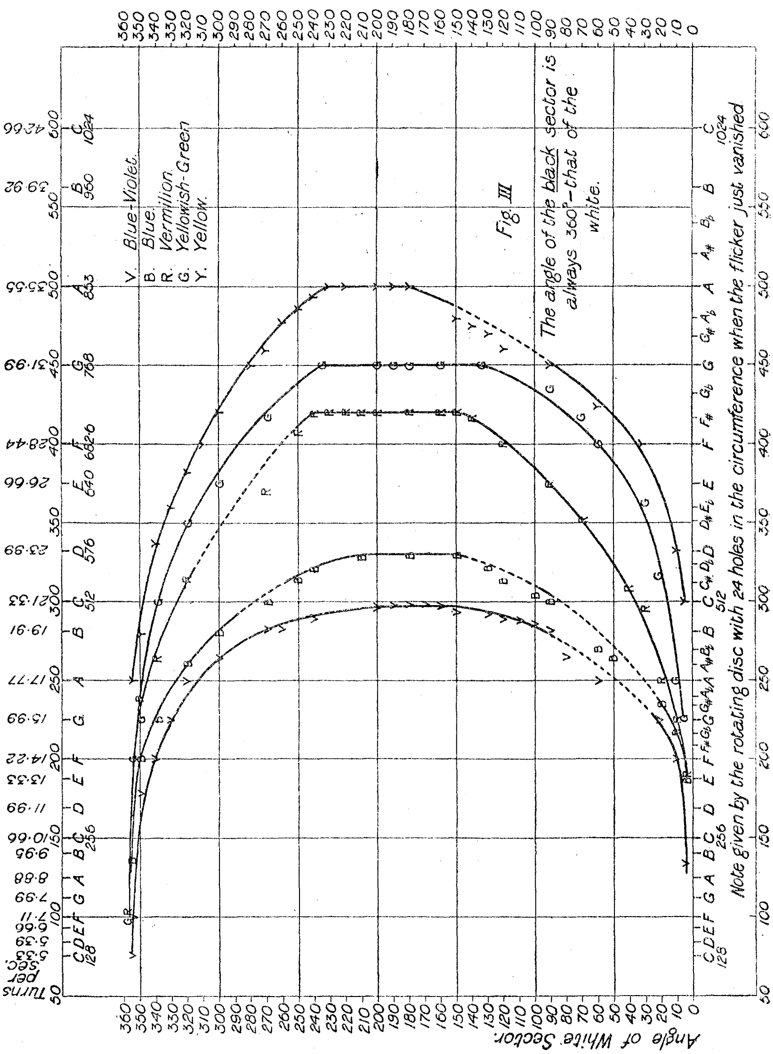
The next point seems to the writer very important, especially with reference to what follows. Numerous experiments were made to find out how the "last" (undiminished) for any one colour varied with the intensity of the light; for the present it is sufficient to say that in every case the more intense the illumination the more rapid must the rotation of the disc be made before flicker will vanish. Hence we are bound to infer that *as the stimulus applied to the retina increases in intensity, the impression produced retains its maximum value for a shorter and shorter time.*

That a brighter illumination does produce a greater stimulus (*i.e.*, that neither the contraction of the pupil, nor any other cause, overcomes the effect of brighter illumination) is conclusively proved by the fact that the brighter the light the brighter on the whole is the disc when flicker has just vanished.

Research was next made to find out in what way the rotation of a disc must be varied for flicker to vanish when the proportion of the coloured to the black sector varied, the intensity of the illumination remaining constant.

Two discs were taken: one painted with Indian ink laid on as dry as possible, and the other of the whitest cardboard procurable; these were dovetailed after Maxwell's method and mounted on a motor with a "syren" disc. This last was pierced with six, twelve, or twenty-four holes, that the note emitted might lie within the octaves which are both easy to sing and in which intervals can be most correctly judged.

As the experiments took many days and nights, and it was most important that the conditions should be as similar as possible on different occasions, the whole of the apparatus remained unmoved throughout the whole set of comparative experiments; the lime-light burner was firmly screwed down to the base-board of the lantern. The rotating disc was most carefully screened from extraneous light, though if the writer repeated the experiments he would wear a black mask to prevent the illumination of the dark sector of the disc by even the faint light reflected from the observer's face. The writer thinks this may account partly, though not wholly, for the asymmetry of the curves of fig. 3 in the case of the red and yellow. The grating was surrounded by a screen coated with the dullest optical black, whilst another screen allowed only the special colour required to fall on the half of the disc viewed. Each observer regarded the




disc from practically the same stand-point and distance, the latter being that of most distinct vision; moreover, he kept his eyes fixed on the same part of the disc, so that the image of the disc did not travel over the retina. All these are important details as will appear later.

Before examining the curves in fig. 3, consider a disc rotating under a fixed degree of illumination, *i.e.*, in a light of constant intensity. Suppose that the light is of a certain colour, *e.g.*, yellow, and that a

certain sector only, reflects the yellow light to the eye, the rest of the disc being of a perfect black. Let the disc be rotating very slowly: then, as the yellow sector passes before the eye, it will appear as bright as possible under the given illumination, *i.e.*, it will appear of no less bright a yellow than it would, if the whole disc were yellow, *i.e.*, the stimulus given to the part of the retina on which its image rests, is the maximum possible to this yellow, under this particular and constant illumination. Now, suppose the rate of rotation to be raised until flicker has just vanished, no part of the disc now looks so bright as the sector did at first, and since the final brightness of the disc varies directly as the width of the yellow sector (this is the fundamental assumption on which all the colour equations rest, and is verified by experiments described later), then, *when the flicker has vanished, the effective stimulus at any point of the retina is to the original and maximum stimulus as the angle of the yellow sector is to the angle of the whole disc, i.e.,* 360°, *the illumination being constant throughout.*

Moreover, since the mere increase in the rate of rotation has no effect whatever on the *real* width and brightness of the yellow sector, but only diminishes the time during which its stimulus is applied to the retina, and diminishes, *in the same ratio*, the time the black sector takes to pass (and the more rapid passage of the black sector must, considered *alone*, tend to *increase* the brightness of the disc), whilst it (the increase in rate of rotation) *increases* to the same extent the *number* of stimuli applied to the retina per second, and the number of transits of the black sector; it follows, since the final apparent brightness of the disc is less than if it were *all* yellow, that *the yellow sector requires a finite time in order to produce its maximum effect, and the same argument applies to any colour.* This conclusion is in complete accordance with the results of other experimentalists.

But this is not all that these considerations prove: for since the increase in speed of rotation diminishes *in the same ratio* both the time the image of the yellow sector takes to pass over a point on the retina, and also the time the image of the black sector takes to pass (*i.e.*, the time the sensation evoked by the yellow sector must necessarily last undiminished, if there is to be no flicker), the increased speed would have no effect whatever on the *flicker* except to multiply the number of times it occurred per second, if it were not that a weaker stimulus has a longer "last" (using the word "last" to mean the duration of the sensation undiminished, after the stimulus has been withdrawn). This is a second proof of the principle established in a different way earlier in the present paper (p. 351).

Experiments were next made to measure directly the apparent brightness of rotating *flickerless* discs, and to find an expression for

the effect of successive equal increments to the bright sector. The method used was to measure the distances from a movable source of light, of the rotating disc, and of a fixed disc, of the same colour as the bright sector of the rotating disc, when the brightness of the two discs appeared equal. It was found that for illuminations about the same as those used in the other experiments recorded in this paper, the law which connects the apparent brightness with the width of the bright sector is that enunciated before, *i.e.*, that a flickerless half-and-half disc appears half as bright as the fixed and wholly white or coloured disc, at any rate within the errors of experiment which, however, in this part of the research were not inconsiderable. When the width of the white or coloured sector was increased in steps of 10° at a time, the *increment* of the apparent brightness in the flickerless disc followed, within the errors of experiment, the series 1/0, 1/1, 1/2, 1/3, 1/4, &c., as it should; and since these fractions express the *ratio* between the increase of stimulus caused at any stage by an additional 10° of coloured sector, and the stimulus already existing before its addition, it follows that we can, with the help of the principles established already, predict how the rate of rotation for the disappearance of flicker must vary with the growth of the white or coloured sector. We should expect the first few additions of the 10° to produce the most marked alteration (a rise, as we already know) in the rate of rotation necessary for the disappearance of flicker, since the diminution in the amount of the black sector is trifling in comparison with its total width. Towards the *final* additions of 10°, we shall reach a stage when the effect of the increment of 10° of white or colour is almost negligible in comparison with the total width of the white or coloured sector, but just at this time, the *relative* diminution of the black sector will be most rapidly *increasing*, and in order that flicker may only just be invisible, the rate of rotation must be considerably diminished, and this diminution will bear to the total velocity almost the ratio the diminution of the black sector (10°) bears to its total width; but not *exactly* this ratio, for since the effective stimulus is still increasing, though the increase is small compared with its total magnitude, and since this implies—apart from any effect of change in the width of the black sector—that the rate of rotation must be raised for the flicker to vanish, it follows that the rate of rotation will not diminish at so rapid a pace as the shrinkage of the black sector's width would demand, if it alone had to be considered. So far, therefore, the "flicker" curve (for a disc with a growing white or coloured sector, the angle of the bright sector being measured on the axis of Y, and the speed of rotation on the axis of X) will be, on the whole, symmetrical with respect to the straight line passing through the point on the axis of Y correspond-

ing to the half-and-half disc, but not completely so, for the consideration just mentioned would cause the curves which are represented in fig. 3 to be steeper on the right than on the left, viewing the curves from the axis of Y. It will be seen at once that in practice the converse is true, and the writer believes that this is due to the fact that the black sector is not completely black. The effect of the small percentage of light reflected from the black sector will be at first to diminish the rate of growth of the speed necessary for flicker to vanish, for it diminishes the contrast between the coloured sector and the black—a contrast on which the flicker primarily depends. The curves will therefore rise more gradually on the right, holding the figure as already described. When there is little of the black left, there will be proportionately little of the light reflected from it,—and if this light be bright enough to have any appreciable effect, the effect must be to make the decrease of the speed of rotation (necessary to cause the flicker to all but reappear) more rapid, because it lessens the effect of the narrow black sector left, giving the impression that all the coloured sector's light has survived the passage of the black sector, for a rate of rotation at which, in reality, a part failed to survive, and would have produced flicker if unaided by the light reflected from the black sector.

Thus any want of blackness in the black sector will have considerably more effect during the early part of the growth of the coloured sector, whilst the black sector is very large, than afterwards, and this completely explains the observed departure from symmetry in the curves constructed from actual observation. It should be noted that from the way in which the disc is illuminated by the spectrum, any light reflected from the black sector is of the same colour as that of the bright sector. If pigment had been used to colour the bright sector, and the disc viewed in white light, white light would have been reflected from both the coloured and the black sector, and the effect of this would be very much harder to explain.

Five curves will be seen in fig. 3; they are for different colours of the same lime-light spectrum; each of the capital letters gives the exact result of an observation, carefully verified in every case. The actual number of rotations per second can be easily found for any point on the curves by dividing the number of vibrations of the corresponding note found on the axis of X by 24, the number of holes in the syren disc. The musical intervals, so far as the diatonic scale is concerned, are the true chromatic, and not the equal temperament system.

The information conveyed by the position of any point on one of the curves may be stated as follows, taking, for example, G on the 160° line of the yellowish-green :—

The excitation of the retina caused by the stimulus of the yellowish-green light of the lime-light spectrum, reflected from "white" cardboard in 1/72 sec. (*i.e.*, 160/360 of 1/32) lasts undiminished for 5/288 sec. (*i.e.*, 200/360 of 1/32), *i.e.*, about 1/58 sec.

Taking the next point G (180°) above this last point, we find that the "last" of the stimulus of the same yellowish-green, applied for 1/64 sec. is 1/64 sec. Thus, tabulating the results for a few more points including the above two,

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Stimulus for | Y.G. applied | 1/72 | sec. lasts | 5/288; | & | $288/5 \times 72/1$ | = 4147 |
| ,, | ,, | 1/64 | ,, | 1/64 | ,, | $64 \times 64$ | = 4096 |
| ,, | ,, | 1/58 | ,, | 1/72 | ,, | $58 \times 72$ | = 4176 |
| ,, | ,, | 1/49 | ,, | 1/92 | ,, | $49 \times 92$ | = 4508 |
| ,, | ,, | 1/40 | ,, | 1/120 | ,, | $40 \times 120$ | = 4800 |
| ,, | ,, | 1/32 | ,, | 1/160 | ,, | $32 \times 160$ | = 5120 |

Hence the duration of the impression on the retina *undiminished* appears to decrease as the time of stimulation increases, though within narrow limits of variation one of these quantities is nearly inversely proportional to the other.

With regard to the *total* duration of a luminous impression, the writer would point out that nothing has been said in this paper; the few experiments he has made to measure this, lead to the belief that it is almost of a different order of magnitude from the time during which an impression remains undiminished, and is to be measured by whole minutes rather than by small fractions of a second.

## "On the Kathode Fall of Potential in Gases." By J. W. Capstick, M.A., D.Sc., Fellow of Trinity College, Cambridge. Communicated by Professor J. J. Thomson, F.R.S. Received May 17,—Read May 26, 1898.

It has been shown by Hittorf* that when an electric current passes through a tube containing a gas at a pressure of a few millimetres, there is a rapid fall of potential near each of the electrodes, with a much more gentle fall in the space between, and whilst the fall near the anode and in the positive column varies with the density of the gas and the current strength, the fall near the kathode is constant. Warburg† has made careful experiments on the kathode fall, and has fully established its constancy. If the gas is pure and dry, the electrodes clean, and of a metal not acted on chemically by the gas,

* 'Wied. Ann.,' vol. 20, p. 705.

† 'Wied. Ann.,' vol. 31, p. 545; vol. 40, p. 1.